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Effects of Magneto-Dielectric Ceramics for Small Antenna Application

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Abstract – Hexagonal Ba-ferrites are widely suggested as materials for small antennas. In this paper, the sintering behavior and magneto-electric properties of $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ($0.1 \leq x \leq 0.5$) ceramics were investigated for small antenna application. All samples of $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics were prepared by the solid-state reaction method and sintered at 1250℃. From the XRD patterns of the sintered $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics, the Z-type phases were found to be the main phases. The real part of permittivity and permeability of the $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics decreased with frequency. On the other hand, loss tangents of permittivity and permeability tended to behave opposite to real part of permittivity and permeability. The real part of permeability was affected by Mn additions. The real part of permittivity, the loss tangent of permittivity and the real part of permeability, the loss tangent of permeability of $Ba_3Co_{0.2}Mn_{0.8}Fe_{24}O_{41}$ ceramics were 19.774, 0.176 and 15.183, 0.073, respectively, at 510 MHz. In order to investigate the effect of magneto-dielectric ceramics on antenna, PIFA (Planar Inverted F Antenna) was simulated with CST (Computer Simulation Technology). The operating frequency of antenna was decreased without considerable change of bandwidth by using the $Ba_3Co_{0.2}Mn_{0.8}Fe_{24}O_{41}$ ceramics as the carrier.

Keywords: Magneto-dielectrics, Co_2Z ferrite, Small antennas, Bandwidth

1. Introduction

With the rapid advancement of mobile communication systems, various services have been required and subsequently realized for mobile phone applications. Trends in miniaturization and high-efficiency have led to the miniaturization of antennas. These improvements of the antenna had limited with only circuit application. Antennas have been miniaturized by using various methods – using meander lines or slots, dielectric loading, and so on [1]. Size reduction of the antenna leads to decreased bandwidth. Size reduction using meander lines or slots degrades antenna performances such as a bandwidth and efficiency. The dielectric loading technique degrades antenna performance and consequently, limits the increase in permittivity. A thick dielectric substrate increases the surface wave energy or stores the energy within itself to decrease the antenna gain. Magneto-dielectric materials raise the hope that the fundamental limitations on electrically small antennas might be abrogated. Electrical wavelength, size and bandwidth of an antenna are related to relative permittivity (ε) and relative permeability (μ) [2]. The operating frequency and bandwidth of an antenna are determined as follows [3].

$$f \approx \frac{c}{2L\sqrt{\varepsilon\mu}} \tag{1}$$

$$BW \approx \frac{96\sqrt{\mu/\varepsilon}\,\frac{t}{\lambda_0}}{\sqrt{2}\left[4+17\sqrt{\mu\varepsilon}\right]} \tag{2}$$

where, c is the velocity of light, L is the length of a patch, t is the thickness of the substrate and λ_0 is the wavelength in free space.

From the equation of the operating frequency and bandwidth, high permittivity or high permeability materials would be preferable for antenna size reduction but they would also decrease the bandwidth or increase the loss tangent, respectively. However, materials which have relatively high and similar values of permittivity and permeability can reduce size without decreasing bandwidth. Hexagonal Ba-ferrites are widely suggested as materials for small antennas. There are several type of Ba-ferrites: M-type ($BaFe_{12}O_{19}$), W-type ($BaM_2Fe_{16}O_{27}$, M : Co, Zn etc.), Y-type ($Ba_2M_2Fe_{12}O_{22}$) and Z-type ($Ba_3M_2Fe_{24}O_{41}$), which all depend on the composition ratio. These ferrites have different crystal structures [4]. Among these Ba-ferrites, the Co_2Z ferrite ($Ba_3Co_2Fe_{24}O_{41}$) has a relatively high permeability and resonance frequency. However, the single phase of the Co_2Z ferrite cannot be synthesized easily because of its complex crystal structure [5].

In this study, we investigated the structural and microwave properties of Mn added Co_2Z ferrite, $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ($0.1 \leq x \leq 0.5$), according to sintering

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temperature and amount of Mn addition. All magnetic ceramics were prepared by the solid-state reaction method. Microstructural and microwave properties were investigated using X-ray diffraction patterns (XRD), scanning electron microscopy (SEM) and a network analyzer.

2. Experiment

In this paper, all samples of $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics were manufactured by the solid-state reaction method and their microwave characteristics were estimated by using the HP network analyzer.

2.1 Manufacturing of samples

The starting materials for the synthesis of the samples were highly purified $BaCO_3$, CoO, MnO and Fe_2O_3 with purity higher than 99.9%. The purified $BaCO_3$, CoO, MnO and Fe_2O_3 were stoichiometrically weighed and ball-milled for 24 hours with alcohol medium and zirconia balls to form the $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ($0.1 \le x \le 0.5$) powders. The mixed powders were dried and calcined at 1000℃ for 3 hours. The calcined $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ powders were re-mixed for 12 hours. The re-mixed powders were uniaxially pressed into a toroid of 5 mm in inner diameter and 10 mm in outer diameter under the pressure of 1 ton/cm^2. The toroid was sintered in air at 1250℃ for 3 hours and polished.

2.2 Measurements

The bulk densities of the polished samples were measured using the Archimedes method with distilled water. The crystalline structures were analyzed by X-ray diffraction patterns using CuKα emission. The power of the X-ray was 20 kV/ 20 mA and the step size and scan speed were 0.1 degree and 2 degree/min., respectively. The microstructures of the polished and thermally etched surfaces were observed by the scanning electron microscope (SEM). The relative permittivity (ε′), relative permeability (μ′) and loss tangents (ε″/ε′, μ″/ μ′) were measured using the coaxial air-line method [6] and calculated by the NRW algorithm [7, 8]. A HPE5071B network analyzer was used to measure microwave characteristics.

3. Results and Discussions

The X-ray diffraction patterns of the $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics sintered at 1250℃ are depicted in Fig. 1. The Z-type, Y-type and W-type phases existed in the calcined $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ powders [9~11]. These XRD patterns matched phase diagram of the BaO-CoO-Fe_2O_3 ternary system [12]. The diffraction peaks of the $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics sintered at 1250℃ were similar to the peaks of a sample of commercial barium hexagonal ferrite (Trans-tech Co.). The sintered specimens showed the Z-type phase as the main phase and showed no secondary phases. These results were due to the sufficient heat energy of 1250℃ to form the Z-type phase, which had a complex crystal structure. The two secondary phases, which showed up in the calcined powders, combined together to form a new Z-type phase in the sintered ceramics. Mn addition did not induce additional new phases or secondary because Mn did not exist as a new phase but at a permeated Co site. These results show that Mn additions do not change the crystal structure of $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics.

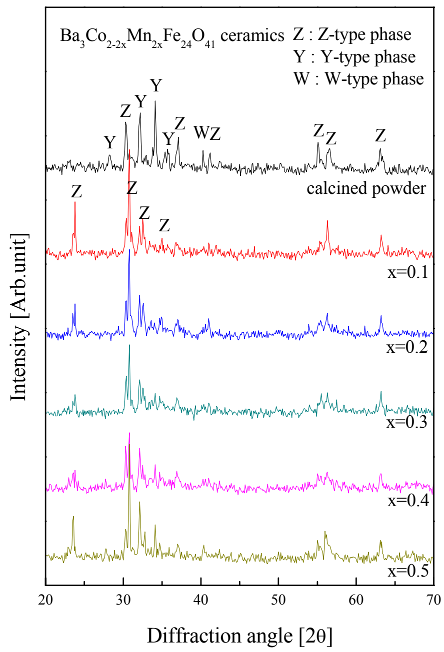


Fig. 1. X-ray diffraction patterns of $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics.

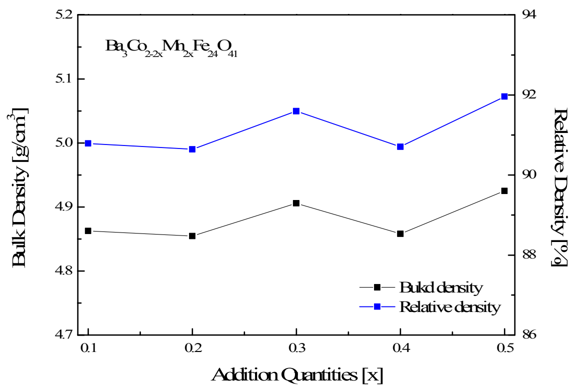


Fig. 2. Bulk and relative densities of $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics.

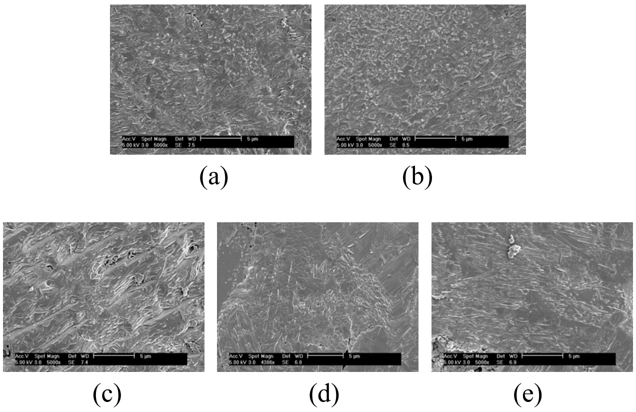


Fig. 3. SEM images of $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics: (a) x = 0.1, (b) x = 0.2, (c) x = 0.3, (d) x = 0.4, (e) x = 0.5.

Fig. 2 shows the bulk densities of $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics with addition ratio. There was no significant difference due to Mn additions. It was hard to judge directly the sinterability of $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics with relatively density because Mn substitutes at the Co site. However, as shown in Fig. 1, there were no differences between crystal structures by Mn addition. Also, the $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics has relatively density of 90% up in spite of molecular weight of Mn (M.W. : 54.94) has lower value than Co (M.W. : 58.93). From these results, it seems that the $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics were fully sintered at 1250℃. These were proved by SEM images (Fig. 3) which shows a dense microstructure without pores.

The real part of permittivity and the loss tangent of permittivity of the $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics are shown in Fig. 4. Generally, the permittivity of a dielectric, including the ferrites, decreases depending on the increasing frequency. The rate of decrease is determined by the composition of the material. In the case of ferrites, some soft ferrites show a gradual reduction of permittivity [13] whereas hard ferrites show a sharp decline [14] depending on the frequency. The real part of permittivity of the $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics decreased with frequency because of the dielectric dispersion, which is proportional to the frequency. Furthermore, the real part of permittivity showed no significant difference with the composition ratio. The real part of permittivity of the $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics showed a higher value than that of $Ba_3Co_2Fe_{24}O_{41}$ ceramics [15].

As shown in Fig. 3, all samples had a dense microstructure having no porosity which had low dielectric constant of $\varepsilon_r = 1$. In these results, it is considered that the real part of permittivity was affected by not porosity but Mn additions. The loss tangent of permittivity, however, showed an opposite tendency to real part of permittivity. The loss tangent of permittivity increased with frequency because of the increase in the dielectric dispersion with frequency. There is no notable difference in terms of loss

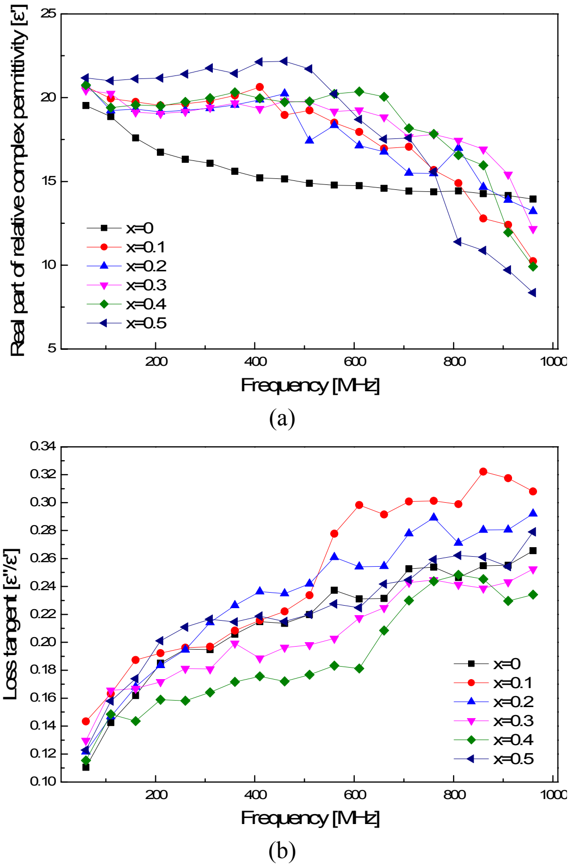


Fig. 4. (a) Real part, and (b) loss tangent of permittivity of $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics.

tangent of permittivity with composition ratio. This is caused by absence of any microstructure defects which have influence on dielectric properties by satisfaction of the Hume-Rothery rule [16].

Fig. 5 shows the real part of permeability and the loss tangent of permeability of the $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics. Essentially, the hexagonal ferrite is anisotropic with one axis and plane which occur the magnetic circulation existed perpendicular to this axis. Therefore, the hexagonal ferrite can have a high relative permeability to overcome the Snoek's limitation [17]. The real part of permeability of the $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics decreased rapidly over 510 MHz and had an inflection point around 800 MHz. Generally, the relative permeability decreases rapidly and has an inflection point above the magnetic resonance frequency. In our result, the magnetic resonance frequencies of the $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics were about 700~800 MHz. The real part of permeability of the $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics showed higher value than of $Ba_3Co_2Fe_{24}O_{41}$ ceramics (14.218 at 210 MHz). This phenomenon could be explained by the lower nuclear magnetic moment of the added Mn (3.4532 μ/μ_N) has than Co (4.627 μ/μ_N), which increased the total magnetic momentum by reduction of destructive interference between the spins of neighboring ferromagnetic atoms. On

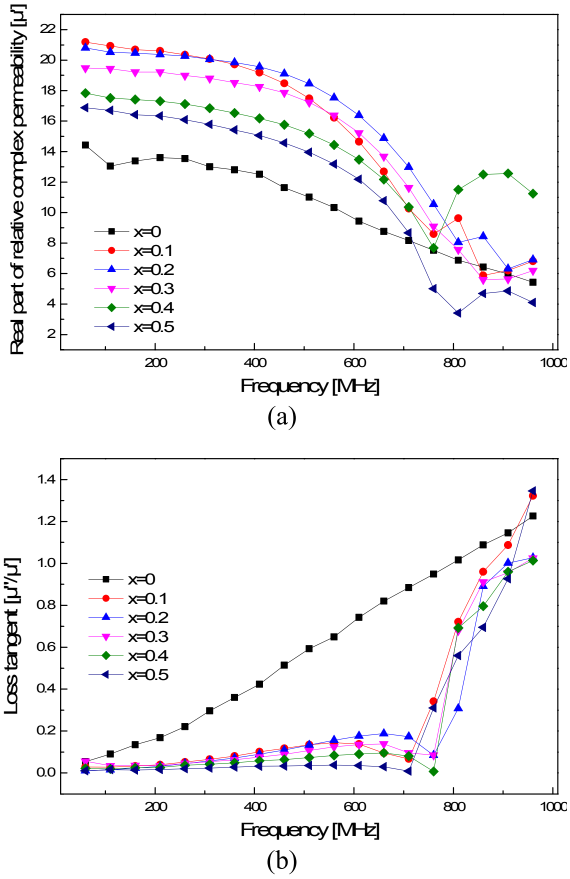


Fig. 5. (a) Real part, and (b) loss tangent of permeability of $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics.

the comparison between the Mn-doped specimens, the real part of permeability decreased with Mn additions because of the low nuclear magnetic moment of Mn. The loss tangent of permeability increased with frequency. This phenomenon was similar to that of loss tangent of permittivity and was due to the increase of dispersion with frequency. The frequency region which shows a rapid increase in the loss tangent of permeability moved to 700~800 MHz by Mn addition because the magnetic resonance frequency was changed. The loss tangent of permeability showed no significant differences with the composition.

The real part of permittivity, loss tangent of the permittivity and real part of permeability, loss tangent of the permeability of the $Ba_3Co_{0.2}Mn_{0.8}Fe_{24}O_{41}$ ceramics sintered at 1250℃ were 19.774, 0.176 and 15.183, 0.073, respectively, at 510 MHz.

To investigate the feasibility of magneto-dielectric ceramics as materials for the antenna component, the antenna was simulated with CST (Computer Simulation Technology), which is used as a 3D electro-magnetic analysis tool. Fig. 6 shows the antenna structure (a) and a detail view of the radiating element (b) with the $Ba_3Co_{0.2}Mn_{0.8}Fe_{24}O_{41}$ ceramics as the carrier. The suggested structure of the antenna was the Planar Inverted

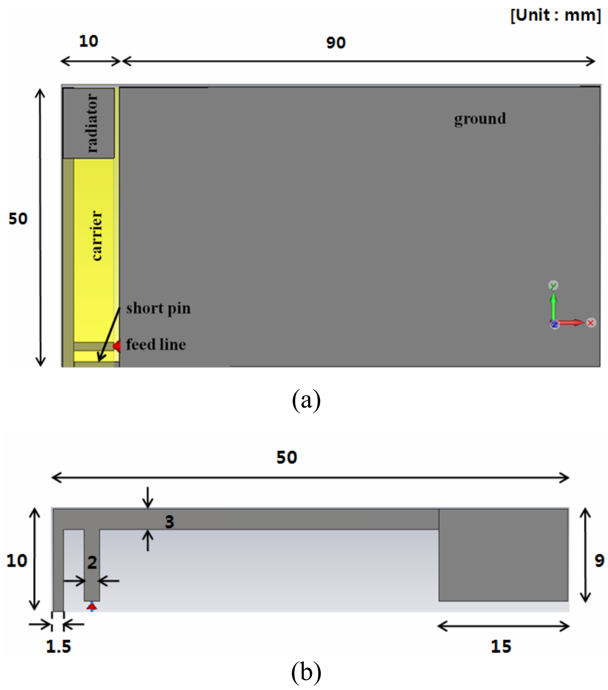
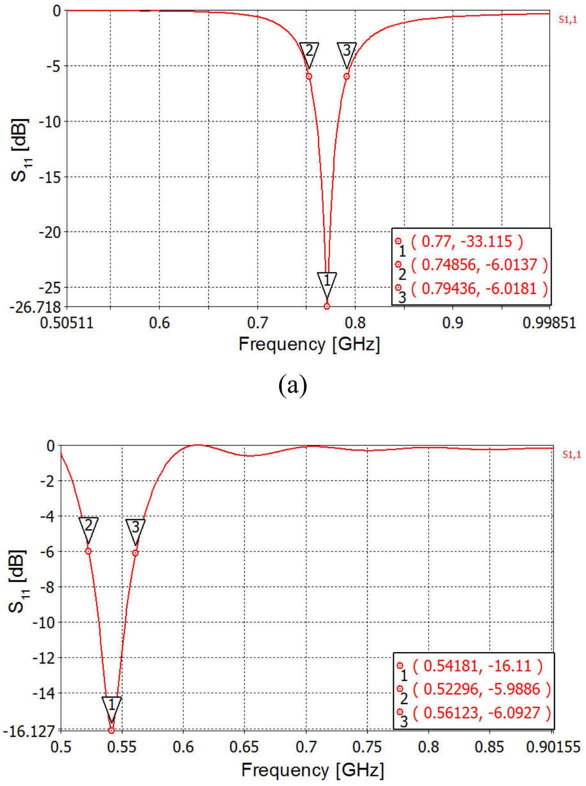


Fig. 6. Suggested PIFA structure: (a) antenna and (b) radiating element

F Antenna (PIFA) structure. The PIFA structure is used for internal antennas because it has advantages such as convenient impedance matching and frequency modulation. PIFA is constructed with a ground, radiator, feed line, short pin and carrier. In an antenna system, FR4 (permittivity: 4.4, permeability: 1) is mostly used as the dielectric material, especially as the carrier material in PIFA, because of its low price. In this paper, we changed the carrier material from FR4 to the $Ba_3Co_{0.2}Mn_{0.8}Fe_{24}O_{41}$ ceramics to confirm the effect of magneto-dielectric ceramics on antenna performance. The size of the designed antenna was $50 \times 10 \times 3$ mm^3 and that of the ground was $50 \times 90 \times 1$ mm^3.

The simulated S-parameter results of the antenna are shown in Fig. 7. With FR4 as the carrier material, the antenna has an operating frequency of 770 MHz and impedance bandwidth (VSWR) of 46 MHz (5.9%). On the other hand, with the $Ba_3Co_{0.2}Mn_{0.8}Fe_{24}O_{41}$ ceramics as the carrier material, the antenna has an operating frequency of 541 MHz and impedance bandwidth (VSWR) of 39 MHz (7.2%). As shown in formula (1), the operating frequency of the antenna shifted to 541 MHz with the $Ba_3Co_{0.2}Mn_{0.8}Fe_{24}O_{41}$ ceramics, which has higher permittivity and permeability than FR4. According to formula (2), the bandwidth of the antenna is directly proportional to the square root of the μ/ε ratio. When dielectric materials are used, the bandwidth decreased because dielectrics have only permittivity. Magneto-dielectric ceramics, on the other hand, have both permittivity and permeability, which do not unduly affect the bandwidth. Also, the antenna seems to show a



(a)

(b)

Fig. 7. Simulated return loss(S_{11}) of PIFA with (a) FR4 carrier material, and (b) $Ba_3Co_{0.2}Mn_{0.8}Fe_{24}O_{41}$ ceramics carrier material.

broadened bandwidth because the magneto-dielectric ceramics, $Ba_3Co_{0.2}Mn_{0.8}Fe_{24}O_{41}$, had relatively higher electric and magnetic loss tangent than FR4 [18]. In this paper, resultantly, the operating frequency of the antenna was decreased without a significant change of bandwidth by the exchange of carrier material. At the same antenna size, the operating frequency was shifted to lower frequency band when the carrier material was changed from FR4 to the $Ba_3Co_{0.2}Mn_{0.8}Fe_{24}O_{41}$ ceramics. So, a miniature antenna could be designed. In other words, we confirmed that the size of the antenna could be reduced by using the $Ba_3Co_{0.2}Mn_{0.8}Fe_{24}O_{41}$ ceramics instead of FR4.

Fig. 8 shows the total efficiency of the proposed PIFA with the $Ba_3Co_{0.2}Mn_{0.8}Fe_{24}O_{41}$ magneto-dielectric ceramics. The total efficiency of an antenna is defined as the radiation power over the input power and it is used to relate gain and directivity [19]. Efficiency was over 25 % in the operation band. The proposed PIFA has lower efficiency than the conventional PIFA because of the loss tangent of the magneto-dielectric ceramics. However, this implies that the proposed magneto-dielectric ceramics can be used for internal Rx antennas such as TDMB (200 MHz) and DVB-h (470~710 MHz) can be applied to the modified magneto-dielectric ceramic loaded PIFA because internal Rx antennas do not need to have high efficiency.

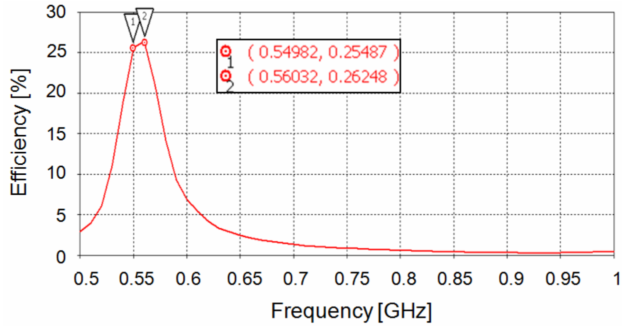


Fig. 8. Total efficiency of PIFA.

4. Conclusion

In this study, the structural and microwave properties of $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics were investigated. All $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics were prepared by the solid-state reaction method and sintered at 1250℃. From the XRD patterns, it was hard to obtain the single phase of Z-type in the calcined powders. However, the single phase of Z-type was formed in most of the sintered specimens. The real part of permittivity decreased and the loss tangent of permittivity increased with frequency. They showed no significant difference with composition ratio. The real part of permeability decreased rapidly over 500 MHz and had an inflection point around 800 MHz.; it also decreased with Mn additions. The real part of permeability of the $Ba_3Co_{2-2x}Mn_{2x}Fe_{24}O_{41}$ ceramics showed a higher value than that of the $Ba_3Co_2Fe_{24}O_{41}$ ceramics. The loss tangent of permeability increased with frequency but showed no significant difference with composition ratio. The real part of permittivity, loss tangent of permittivity and real part of permeability, loss tangent of permeability of the $Ba_3Co_{0.2}Mn_{0.8}Fe_{24}O_{41}$ ceramics sintered at 1250℃ were 19.774, 0.176 and 15.183, 0.073, respectively, at 510 MHz. The simulated PIFA with the $Ba_3Co_{0.2}Mn_{0.8}Fe_{24}O_{41}$ ceramics showed an operating frequency of 541 MHz and impedance bandwidth (Voltage Standing Wave Ratio, VSWR) of 39 MHz (7.2%). The total efficiency of the proposed PIFA was approximately 25% in the operation band. From these results, it seems that the size of an antenna can be reduced by using magneto-dielectric materials instead of FR4, without the decrease of bandwidth.

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